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Interactions of ultrahigh-energy cosmic rays with photons in the galactic center

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Abstract

Ultrahigh-energy cosmic rays passing through the central region of the Galaxy interact with starlight and the infrared photons. Both nuclei and protons generate secondary fluxes of photons and neutrinos on their passage through the central region. We compute the fluxes of these secondary particles, the observations of which can be used to improve one's understanding of origin and composition of ultrahigh-energy comic rays, especially if the violation of the Greisen–Zatespin–Kuzmin cutoff is confirmed by the future data.

Ultrahigh-energy cosmic rays (UHECR) can interact with the cosmic microwave background radiation (CMBR) photons and produce pions. This process, which is the main source of energy losses for the highest-energy cosmic rays, is supposed to result in the Greisen–Zatsepin–Kuzmin (GZK) cutoff [1]. However, observations of ultrahigh-energy cosmic rays (UHECR) show a number of events with energies above 10^{20}eV [2]. While the first data reported by Pierre Auger experiment [3] neither confirm, nor rule out the violation of the GZK cutoff reported by AGASA, one expect much more definitive results in the near future. If UHECR interact with the CMBR, then GZK cutoff will soon be observed and the photons from pion decays should also be discovered in the near future [4].

If, however, the cosmic ray spectrum continues beyond 10^{20}eV without GZK suppression, then either the flux of UHECR is dominated by nearby sources (for example, decaying superheavy relic particles [5,6]), or the photomeson interactions with the CMB photons are stymied by some new physics, for example, a violation of the Lorentz invariance [7]. In either case, the diffuse flux of UHE photons is either small or zero. However, in either case, the UHECR

protons and nuclei can interact with the photons in the galactic center (GC), where the density of photons is very high, and where the average energy of photons is much higher than that of the CMB photons. Detection of photons or neutrinos from UHECR interactions in the galactic center, in the absence of GZK cutoff and diffuse UHE photon flux would be an important indication of new physics.

In this paper we examine the propagation of UHECR through the central region of Galaxy which contains a relatively high density of starlight photons, infrared (IR) photons, and interstellar gas.

The energy and composition of extragalactic cosmic rays passing through the central region of Galaxy can be altered by their interactions with starlight photons and infrared photons emitted by dust reradiation of starlight. Interactions of ultrahigh protons with such photons results in the production of pions [1] which generate a secondary flux of photons and neutrinos [8]. The most important interactions involving ultrahigh energy nuclei are photodisintegration interactions [9], similar to the Zatsepin–Gerasimova effect for interactions with solar photons [10,11,12].

These interactions can be observed in different ways. First, there will be a suppression in UHECR observed in the direction of the central galaxy, but this shadow may be difficult to observe and identify. The detection of UHE photons and neutrinos from interactions of nuclei and protons in the region of the GC presents a more promising study of UHECR. Also, photodisintegration of nuclei can decrease the average atomic weight of UHECR nuclei coming from the direction of the GC, so that one can look for such a change in composition.

Let us now discuss the interactions of UHECR nuclei and protons with starlight. One can model the photon density in the galactic center using a stellar population model based on star counts [13]. In reality the distribution of stars is more complicated, non-uniform, with bright clusters [14] and gaps between them. However, since these bright clusters do not present extensive optically thick targets, we can use a smoothed-out stellar distribution. We assume that all stars have the same average luminosity L_*. Since the angular size of the central core region is not much bigger than the angular resolution of UHECR experiments, we can consider the total photon distribution to be approximately spherical. Let us denote the number density of stars as $n_*(r)$ and the number density of photons as $n_\gamma(r)$. The total number of photons passing through a sphere of radius R centered at the GC per unit time is equal to the total number of photons produced inside such a sphere, $I_1(R)$, plus the photons originating outside the sphere and passing through it, $I_2(R)$:

$$I_1 = \int_0^R 4\pi r^2 L_* n_*(r) dr \tag{1}$$

$$I_2 = \int_R^\infty 4\pi r^2 L_* n_*(r) \left(1 - \sqrt{1 - R^2/r^2}\right) dr \tag{2}$$

The same number of photons can be written as $4\pi R^2 \times n_\gamma(R)$. From the equality of these two fluxes we get an estimate for the number density of photons produced by a given distribution of stars:

$$n_\gamma(R) = \frac{L_*}{R^2} \int_0^\infty n_*(r) f(r) r^2 dr, \tag{3}$$

where

$$f(r) = \begin{cases} 1, & r < R \\ 1 - \sqrt{1 - R^2/r^2}, & r \geq R \end{cases} \tag{4}$$

One can approximate the stellar density as

$$n_*(r) = n_0 r^{-1.8} \exp\{(-r/\mathrm{kpc})^3\}, \tag{5}$$

where $n_0 \approx 0.8 \times 10^6 \mathrm{pc}^{-3}$ [13]. This estimate could be further improved if one needed to take into account the angular distribution at angles much smaller than a degree. One could, for example, use astronomical data from MSX and IRAS surveys and try to reconstruct the photon density based on the photometry data of specific regions in the vicinity of the GC. However, for our purposes the estimate given by eq. 4 is sufficient because we are interested in the effect on UHECR spectrum and composition integrated over approximately one square degree around GC.

The density of IR photons in the Central Molecular Zone (CMZ) [15] is the highest in dense clouds of dust, in which the starlight is absorbed and remitted as the infrared light. Gas and dust in the CMZ have temperatures ranging from 30 K to 200 K, with an average temperature of 70 K [15,16]. We make a simplified model of the IR radiation field near the galactic center by assuming that all the IR photons come from a spherical dust cloud with radius $\approx$ 5pc, centered near GC. The spectrum of IR photons is assumed to be thermal, with temperature 70 K.

Other sources of photons are present in the central region of the Galaxy, but they do not give a significant contribution. For example, a few tens of

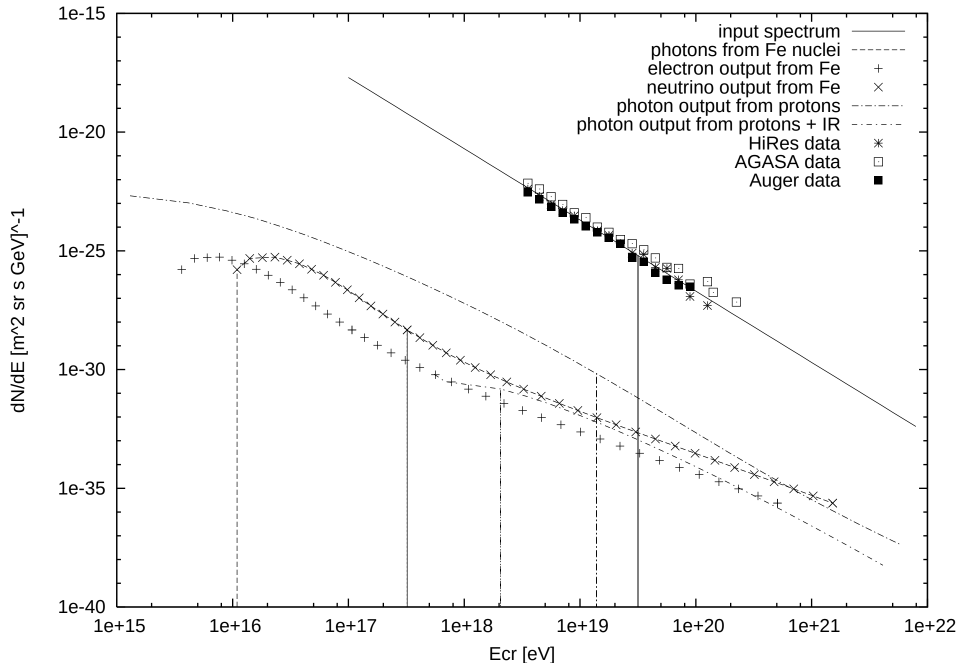

Fig. 1. The spectrum of secondary photons produced by cosmic ray interactions near the galactic center (GC). The fluxes are averaged over a square degree near the GC. The dashed line represents the input spectrum of UHECR, assumed to be a simple power-law without a GZK cutoff (*cf.* Fig. 2). Also shown are the data points from AGASA, HiRes, and Pierre Auger experiments. (These points are the reorted central values drawn to guide the eye; the error bars are not shown.) The solid and the dotted line show the spectra of secondary photons assuming the primaries are protons or iron nuclei, respectively. As discussed in the text, the predicted spectrum of high-energy neutrinos is very close to that of photons.

supernovae happen during the passage of a cosmic ray through the galactic center region, but only those cosmic rays that pass closer than a light-year away from a supernova within the first year since its explosion can interact efficiently with the supernova photons. We estimate that this has a negligible effect on the overall flux.

We have computed numerically the spectra of photons produced by the cosmic rays passing through the central bulge under the assumption that the primaries are (i) protons and (ii) iron nuclei. In reality, one should probably expect the composition to be a mixture of different nuclei, unless the sources are such that they cannot produce UHE nuclei at all (this is the case in top-down scenarios, for example). The resulting spectra are shown in Fig. 1. The injection spectrum of UHECR is assumed to be a simple power-law spectrum, consistent with AGASA and Pierre Auger results [2,3]. Since the photons from the galactic center are of most interest if the GZK cutoff is *not* detected, we have assumed no suppression of UHECR flux at energies beyond 10^{20} eV for fluxes shown in Fig. 1. In Fig. 2 we show our results for the input spectrum that has a GZK cutoff.

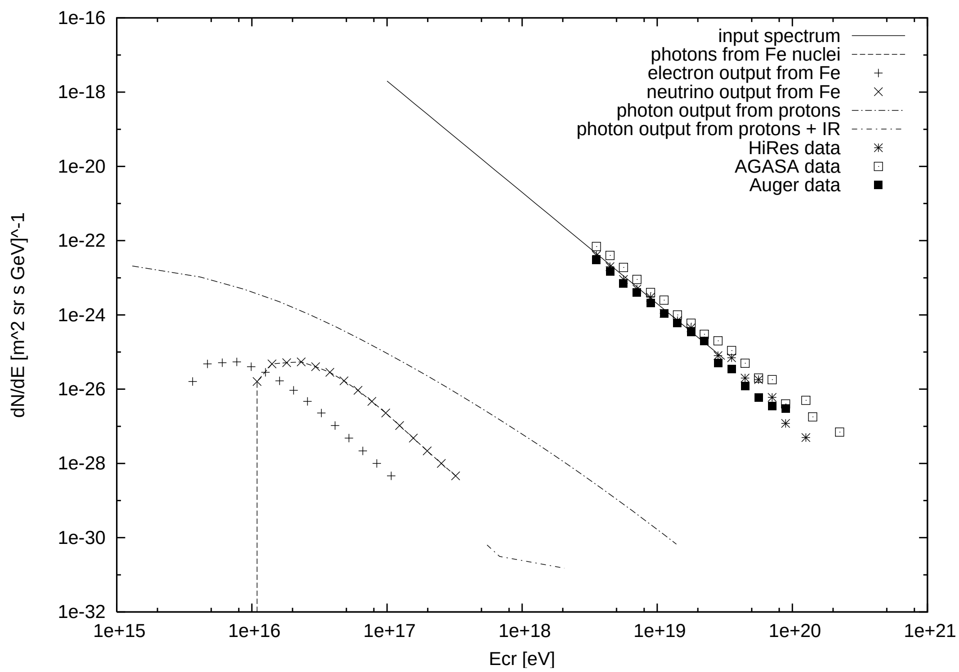

Fig. 2. The spectrum of secondary photons in the case of a sharp GZK cutoff for the input spectrum. If photomeson interactions do take place and produce GZK cutoff, the diffuse photon background exceeds the flux shown here. As in Fig. 1, the fluxes are averaged over a square degree near the GC. The dashed line represents the input spectrum of UHECR, assumed to be a simple power-law. The solid and the dotted line show the spectra of secondary photons assuming the primaries are protons or iron nuclei, respectively.

The photon field near GC is sufficiently thin and is sufficiently close to Earth that one need not include a full cascade calculation. If an UHECR proton interacts with a starlight photon, it produces a pion and either a proton or a neutron in the final state.

The flux of secondary protons is too low to be of interest. Secondary neutrons at these energies do not have enough time to decay. They arrive at Earth unimpeded by cosmic background and undeflected by magnetic fields. If some experiments could distinguish between protons and neutrons, the galactic center would be seen as a source of neutrons. However, both techniques used for the detection of UHECR, the ground array and the fluorescent telescopes, are unable to distinguish a shower started by a neutron from the one started by a proton. Therefore, only the photons and the neutrinos are of interest to us, and only a single interaction of UHECR hadron with a photon needs to be considered.

The spectrum of neutrinos is very close to that of photons shown in Fig. 1. Indeed, one-third of pions produced in photomeson interactions are π^0, and they produce two photons each when they decay. The other two-third of the pions produced in these reactions generate one muon and one muon neutrino

each. These neutrinos have energy spectrum similar to that of photons from π^0 decays. The muon decays produce additional neutrinos at lower energies, but at lower energies they energies they give a small contribution to the neutrino flux. As a result, the high-energy neutrinos have a spectrum that is very close to that of the photons in Fig. 1. Both the uncertainties in the input spectrum and the experimental uncertainties are much larger than the difference between the two fluxes.

In addition to photons and neutrinos, pion decays produce electrons. Experimentally one probably cannot distinguish between atmospheric showers initiated by photons and electrons. As shown in Fig. 1, the electrons do not give an appreciable contribution to the photon flux.

The optical depth of the galactic center region is less than one. If the photomeson interactions of UHECR do take place, then the optical depth of the universe is much greater than one, and the isotropic extragalactic flux of UHE photons [4] exceeds the contribution from the galactic center. However, in the absence of GZK cutoff caused by photomeson interactions, the photons from the galactic center dominate. The angular size of the photomeson region is about $\Omega = 0.03$ sr. Hence, one expects several events per year in Pierre Auger.

For comparison, we also show, in Fig. 2 the fluxes of photons and neutrinos in the case when the input specturm is suppressed for energies beyond the GZK cutoff. Of course, in this case one expects a stronger diffuse photon flux.

One can envision several ways in which the observations of GC can be used to understand the origin and composition of UHECR. If the violation of the GZK cutoff is confirmed by Pierre Auger experiment, one can look at the UHE photon flux. Pierre Auger can identify the photons, and it has set an upper limit of 26% for the fraction of showers caused by primary photo ns at 10^{19}eV [17]. This limit will improve significantly in the near future. If the diffuse isotropic UHE photon flux is detected, it can indicate that photomeson interactions of UHECR with CMBR do take place. A diffuse anisotropic photon flux with about 10% increase in the direction of the galactic center could come from decaying superheavy relic particles in the galactic halo [5]. However, the spectrum of these photons should be much harder than that of the photons shown in Fig. 2. This could be used to distinguish between the two possibilities. Finally, if UHE photons are detected from a small region around GC and no diffuse flux is detected, this would mean that photomeson interactions take place only in the galactic center on starlight photons with energies $\sim$eV, while no pion production occurs on CMB photons. This could be the case, for example, if the Lorentz invariance is broken for high gamma factors [7] in such a way that the CMB photons appear below the threshold for pion production, while starlight photons are above the threshold.

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